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Useful daylight illuminance: a new paradigm for assessing daylight in buildings

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This paper introduces a new paradigm to assess daylight in buildings called 'useful daylight illuminance', or UDI. The UDI paradigm preserves much of the interpretive simplicity of the conventional daylight factor approach. In contrast to daylight factors however, UDI is founded on an annual time-series of absolute values for illuminance predicted under realistic skies generated from standard meteorological datasets. Achieved UDI is defined as the annual occurrence of illuminances across the work plane where all the illuminances are within the range 100–2000 lux. These limits are based on reports of occupant preferences and behaviour in daylit offices with user-operated shading devices. The degree to which UDI is not achieved because illuminances exceed the upper limit is indicative of the potential for occupant discomfort. The relation between achieved UDI and annual energy consumption for lighting is examined.

1. Introduction

The exploitation of daylight, commonly referred to as 'daylighting', is recognized as an effective means to reduce the artificial lighting requirements of non-domestic buildings.[1] In practice however, daylighting is a greatly under-exploited natural resource. Significant amongst the various reasons for this may be the inability of the standard predictive method—the daylight factor approach—to account for realistic conditions. It is recognized that the daylight factor approach offers only a limited insight into true daylighting performance because it is founded on a measure of illumination under a single, idealized overcast sky. The daylight factor at any point in a space is the ratio of the (internal) illuminance at that point to the unobstructed (external) horizontal illuminance under the CIE standard overcast sky. No account is taken of the illuminance from the sun and non-overcast skies, and so the daylight factor is invariant to building orientation. The daylight factor can be determined analytically, from measurements in artificial skies or by computer simulation.

The venerable daylight factor approach is now over 50 years old. It persists as the dominant evaluation metric for daylighting because of its inherent simplicity rather than its 'realism'. Despite the lack of realism, practitioners have become accustomed to the daylight factor and design manuals such as the CIBSE Guide A list recommended minimum daylight factors for various settings or tasks. Indeed, for the vast majority of practitioners, the consideration of any *quantitative* measure of daylight begins and ends with the daylight factor.

Advances in computer simulation allow for the possibility of daylighting analyses that are based on hourly (or sub-hourly) predictions of internal illuminance for a full year.[2,3] For

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these approaches, the hourly sun and sky conditions are derived from basic irradiance quantities found in meteorological datasets known as Test Reference Years (or Typical Meteorological Years in the US). The simulations produce hourly predictions of internal illuminance at each of the calculation points considered. For sub-hourly predictions, short-term variability in basic irradiance quantities can be synthesized using statistical models.[4] Both Mardaljevic's[2] and Reinhart's[3] techniques are based on the daylight coefficient approach[5] and have undergone validation tests. The approach formulated by Mardaljevic has been tested against the BRE-IDMP validation dataset[6] and proven to be highly accurate.

This paper describes various ways in which time-varying daylight illuminance data for an entire year have been analysed and presented. A new schema to assess daylighting potential is described and a new metric called the 'useful daylight illuminance' is presented. Although the new metric is derived from time-varying annual illuminance data, it nevertheless retains much of the interpretive simplicity of the daylight factor.

2. Annual daylighting data

Hourly, or sub-hourly, predictions of daylight illuminance under variable sky and sun conditions can provide a realistic measure of the true daylighting performance for an internal space. Whilst it may be informative to determine, say, a monthly average for a scalar quantity such as temperature, illumination is strongly dependant on the directional character of the incident light. Illumination parameters therefore are generally not suited to manipulations such as averaging. Sub-sampling the meteorological dataset (e.g., taking only the first day of each month) will reduce the number of hours to consider. This action however will inevitably introduce biases because equally valid—but most likely quite different sky and sun conditions and positions—would be excluded. Indeed, it seems that the only way to avoid the pitfalls of averaging or sub-sampling is to consider the meteorological dataset in its *entirety*. That is, all the hourly sky and sun conditions for a period of a full year. Only this can capture the full range of both the short-term and long-term variation in the sky and sun conditions.

The minimum number of predicted illuminances to consider therefore is $\sim$4000 per calculation point for hourly data i.e., this is the approximate number of daylight hours in the year. If the predictions were based on one minute data, then this number would increase by a factor of 60 to $\sim 2.4 \times 10^5$ (per calculation point). These numbers could be made slightly smaller in relative terms by considering only the hours of the typical working day e.g., 9 am to 5 pm, but overall the amount of data will remain large in absolute terms even for just hourly data.

2.1 'Raw' illuminance data

An illustration of the daylight illuminance data that results from an annual simulation is given in Figure 1. Here, the predicted hourly illuminance data for an entire year at just one point in an office space are shown. The 8760 hours for the entire year are shown as (tiny) shaded rectangles arranged in a 365 (days of the year) by 24 (hours of the day) matrix. The shading in Figure 1 represents the magnitude of the predicted daylight illuminance with zero values shaded light-grey. This is the unprocessed, or 'raw' illuminance data viewed in their entirety, for one point in an office space. Presented in this way, it is easy to appreciate both the prevailing patterns in the daylight illuminance and its short-term variability. Most obvious is the daily and seasonal pattern, but it is also possible to discern the hour-by-hour variation. The voluminous 'raw' illuminance data from an annual lighting simulation can be used directly for dynamic energy modelling.[7] The raw data can also be of great value to researchers because

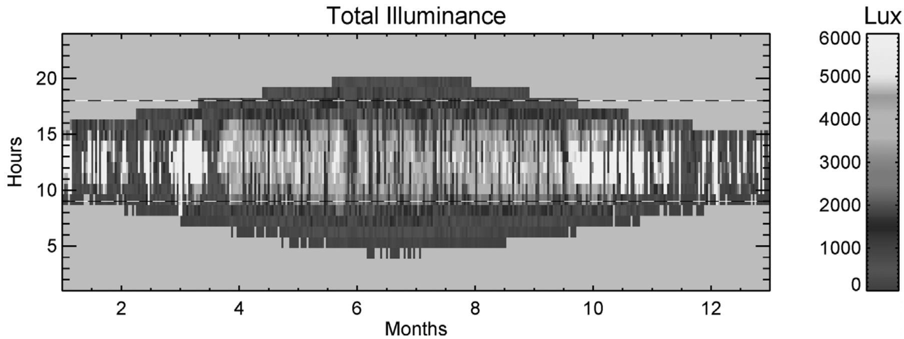

Figure 1 Raw illuminance predictions for one point

they reveal in detail the space–time progression of daylight illumination—a previously hidden quantity. In Mardaljevic's implementation of the daylight coefficient approach, the direct and indirect components of sun and sky light are computed separately.[2] This allows analysis of both the relative proportions and the absolute magnitude of the illuminance components e.g., to examine and fine-tune the ability of a light shelf to redirect sunlight to the back of a room.

For energy modellers and researchers therefore, time-varying daylight illuminance data have much to offer. The majority of building designers and architects however, are likely to consider the mass of illuminance data immense and the level of detail inappropriate, especially at the early design stage. How then can the time-varying daylight illuminance data be processed or reduced to become both more manageable and readily intelligible? The following sections describe various ways in which the raw illuminance data can be analysed and presented. The daylight illuminance data for the examples that follow are predictions for a typical office space obtained by computer simulation using the technique formulated by Mardaljevic[8] and later refined by Nabil.[9]

2.2 The computer model

A simple 3D model of a typical side-lit office space was constructed using *Radiance*'s own scripts and surface generators. The office had the dimensions shown in Figure 2 and was 3 m wide. The reflectivities of the walls, ceiling, and floor were set to be 0.7, 0.8, and 0.2, respectively. The window had standard 6 mm clear double glazing with a transmittance of

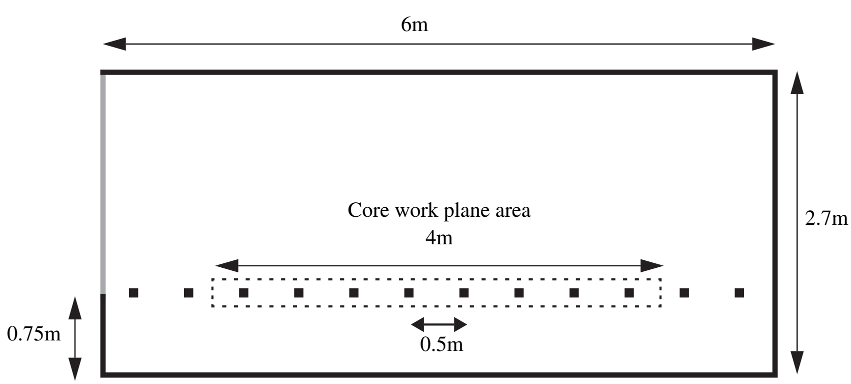

Figure 2 Office model

0.76. The calculation points lay on the work-plane (0.75 m from the floor), along a straight line from the window to the back of the office, as shown in Figure 2. The distance between the window wall and the first point and that between the last point and the back wall was 0.25 m. The distance between consecutive points was 0.5 m. Daylight coefficients (DCs) were calculated for each of these 12 points.

Hourly sky and sun conditions were derived from the direct normal and diffuse horizontal irradiation data in the Kew-84 (51.47°N, 0.28°W) Test Reference Year for every daylight hour in the year (i.e., where the irradiation is greater than zero—out of 8760 hours, there are 4316 daylight hours in this particular TRY). The hourly internal illuminance was derived from the pre-computed daylight coefficients at each of the 12 points in the office. That is, $4316 \times 12 = 51792$ illuminances in total. Note that daylight coefficients are invariant to orientation of the building, allowing illuminances to be derived for arbitrary orientations once the DCs have been computed. In the first instance, the office orientation was set with the window facing due south. Furthermore, once computed, daylight coefficients can be reused with any number of climate datasets to rapidly generate internal illuminance predictions for various locales (see Section 4.2).

2.3 Cumulative illuminances and daylight autonomy

The raw hourly illuminance data given in Figure 1 could be similarly presented for each of the 12 calculation points in the office using a separate plot for each point. Whilst instructive in revealing the patterns of daylight illuminance at a particular point and for a particular window orientation, this type of presentation would be overwhelming and give no sense of how the daylight illuminance varies across the space. One way to reduce the data is to derive the cumulative availability of daylight illuminance from the time-series of hourly values at each point. This gives the number of hours of the year at which any particular daylight illuminance level is achieved. This is commonly presented as a curve showing the number of hours (or percentage of the working year) versus the illuminance level. The daylight illuminance data presented in Figure 1 are shown as a cumulative availability plot in Figure 3. Here it can be seen that a daylight illuminance of 500 lux was achieved for ~70% of the working year (at a point 2.25 m from the window). The

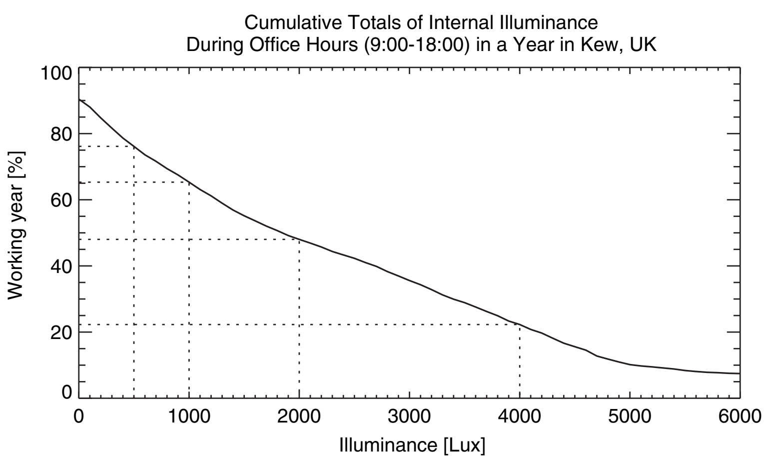

Figure 3 Cumulative curve plot

same information for all the points in the space can be communicated in a single plot by forming the individual cumulative data into a 2D array and using either shade or contours to indicate the percentage of the working year, Figure 4. Here, both shade and contour lines were used, and the illuminance range shown was truncated to 2000 lux. Now, the distribution in daylight availability across the entire office space is readily apparent. Dotted lines in Figure 4 mark threshold illuminances of 500 lux, 1000 lux, and 1500 lux (horizontal lines) and positions on the workplane 1 m, 3 m, and 5 m. from the window (vertical lines). These positions on the workplane were considered as representatives of the front, middle, and back of the office, respectively.

One measure of daylight availability is how many hours per year a predefined minimum illuminance level is achieved at the workplane. This information can easily be drawn from the cumulative availability plots and is sometimes referred to as 'daylight autonomy'. The minimum daylight illuminance is usually taken to be the desired illuminance level for office tasks i.e., 500 lux. Reading from Figure 4, an illuminance of 500 lux is exceeded for ~84% of the working year at the front of the office, ~70% in the middle, and ~55% at the back. Thus, in principle, the office space used for this example could be adequately illuminated by daylight alone for the majority of the working year.

2.4 Distribution of the absolute levels of daylight illuminance

Whilst the cumulative plot shows how often a target illuminance was achieved by daylight alone, the degree to which the target illuminance was exceeded is not disclosed. Thus it is not possible to easily infer from cumulative plots what the absolute values of daylight illuminance were. Although truncated to show a maximum of 2000 lux, the contour curves in Figure 4 clearly indicate that much higher daylight illuminances are achieved for considerable periods of the year, particularly at the front of the office. A more informative, yet equally synoptic, overview of the illuminance data can be obtained from the frequency of occurrence of daylight levels within specified bands. For this, the illuminance data were sorted into nine contiguous bins that covered the entire range in predicted illumi-

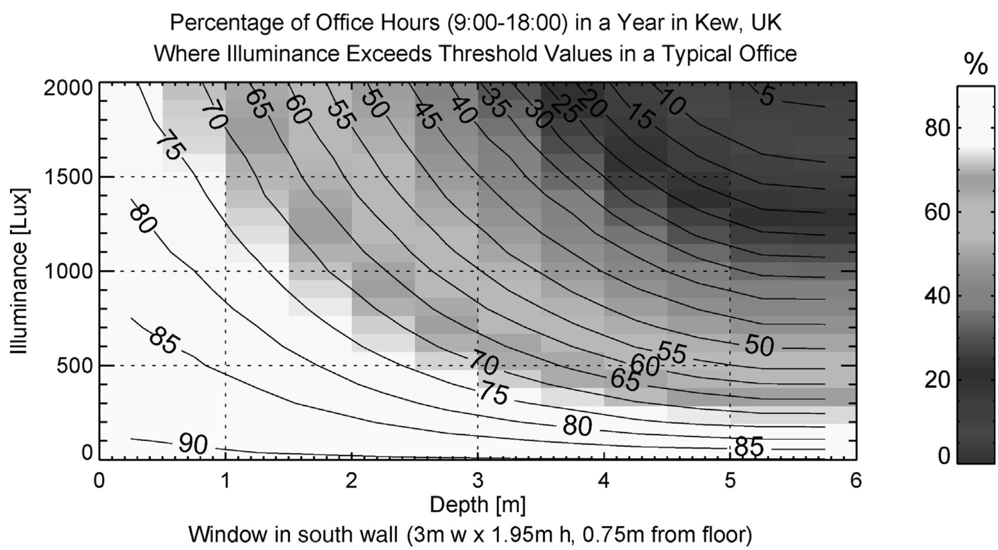

Figure 4 Cumulative illuminance availability for a line of 12 points on the workplane with a window facing due south

nances from zero upwards. In contrast to the more usual presentation for a frequency histogram, a variable bin width was used as this better revealed the wide range in the predicted daylight levels. The frequency of occurrence for a particular bin (as percentage of the working year) is indicated by the vertical extent of the bin. These are 'stacked' one on top of the other so that the total will always equal 100%. The plot for the entire space is given in Figure 5. The range for each bin is given in the plot legend. Note, the order in the stacking at any one calculation point has no significance. However, maintaining the order from one calculation point to the next does reveal the continuous variation in the frequency of occurrence across the space. To aid this, the boundary between the bins is drawn as a curve *across* the calculation points from the front to the back.

From the cumulative plot (Figure 4), 500 lux was achieved in the middle of the office for ~70% of the working year. However, the 'stacked' plot (Figure 5) shows that for ~35% (of the working year) the daylight illuminances were *greater* than 2000 lux. Studies indicate that in practical situations, such levels of daylight illuminance are considered too high for occupants' comfort—both visual and thermal.[10] As a result, the occupants are likely to resort to operating some kind of blinds or shades on the window thus decreasing the amount of daylight admitted into the office as a whole. Where blinds are not available, they may resort to *ad hoc* solutions such as pasting paper or card onto the glazing. Consequently, electric lights may be switched on to compensate for the decreased daylight illumination. When occupant behaviour is considered, the daylight autonomy levels suggested by the cumulative plot do

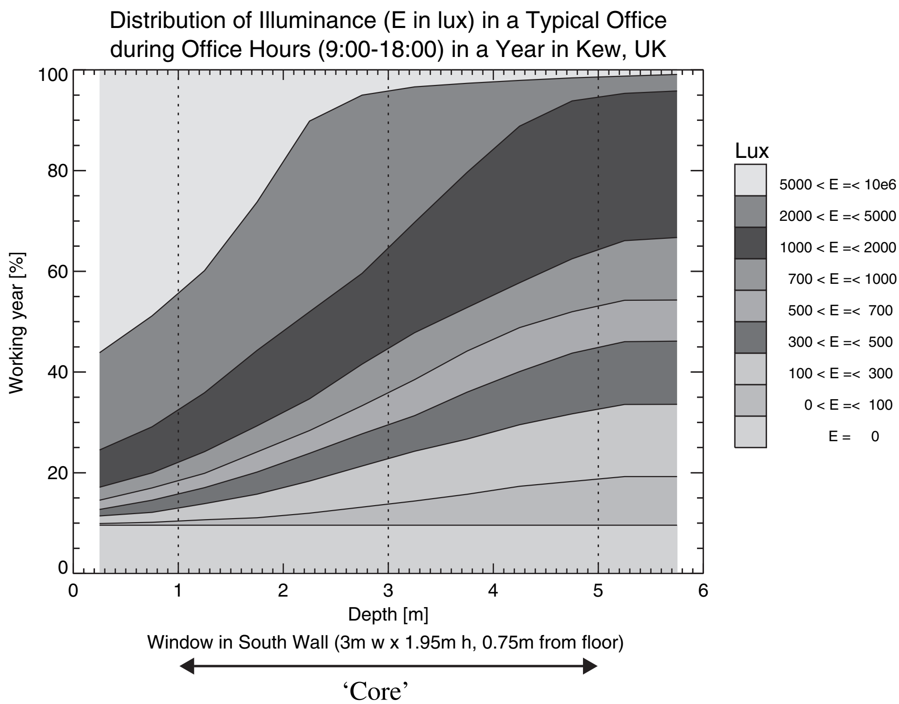

Figure 5 Stacked illuminance distribution

not seem so promising, and indeed much of the hoped-for savings in electric lighting are often non-attainable in practice.

The above highlights the shortcomings of evaluations that assess daylight illuminance at one calculation point independently of the others. Comfortable daylight illumination ($\sim$500 lux) at the back of the office may often occur at the expense of occupant discomfort ($>$2000 lux) at the front.

A realistic evaluation of time-varying daylight needs to take some account of how occupants might respond to high and low levels of daylight e.g., by lowering blinds and switching on lights. The evaluation should therefore consider the simultaneous occurrence of daylight illuminance across the space, rather than at the points independently. Also, the evaluation should, ideally, result in a summary metric that manages to describe the overall daylighting performance of the space. A new schema to interpret daylight illuminance data that possesses these attributes is described in the next section.

3. The concept of 'useful daylight illuminances'

Daylight illuminances across the work plane of a typical side-lit office space can vary by an order of magnitude or more from the front (near the window) to the back. Notions of illuminance uniformity that come from using the standard overcast sky paradigm are inapplicable for realistic conditions where the contribution of direct sunlight leads to large differences between the maximum and minimum daylight levels. Accordingly, any proposed metric that is designed to take measure of realistic time-varying daylight illuminances must accommodate in some way the huge range in levels that occur. This can only be achieved by abandoning the notion of a target illuminance e.g., 500 lux, and determining instead the occurrence of a range of illuminance levels, across the work plane, that can be said to constitute *useful* levels of daylight illuminance. If the daylight illuminance is too small (i.e., below a minimum), it may not contribute in any useful way to either the perception of the visual environment or in the carrying out of visual tasks. Conversely, if the daylight illuminance is too great (i.e., above a maximum), it may produce visual or thermal discomfort, or both, causing the occupant(s) to trigger the operation of blinds etc. Illuminances that fall between the bounds of minimum and maximum are called here *useful daylight illuminances*. The absolute values assigned to the minimum and maximum illuminance levels are based on a survey of published work on occupant behaviour in daylit office environments under a wide range of illumination conditions. How the minimum and maximum illuminance levels were arrived at is described in the following section.

3.1 Occupant response to daylight levels: a brief survey of published work

There is a large range of lighting conditions over which the human eye performs satisfactorily, and there is a large range of variation among individuals as to what comprises satisfactory conditions.[11] While there are no conclusive studies which correlate daylighting provision, occupant satisfaction with the environment and worker productivity, there is anecdotal evidence that workers appreciate offices that provide daylight and a view of the outside, and that glare-free and thermally comfortable spaces have quantifiable effects on workers' satisfaction and performance.[12,13]

The UK Chartered Institution of Building Services Engineers (CIBSE) Code for Interior Lighting recommends that offices should have a design illuminance level of 500 lux. A design illuminance of 500 lux is commonplace throughout much of the developed world. Accordingly, electric lighting is usually designed to deliver 500 lux of (artificial) illuminance evenly across the work plane. Where sufficient daylight is available, electric lighting may be reduced or switched off altogether by either the occupants themselves or some control mechanism.

It was noted in the Cost-Effective Open-Plan Environment (COPE) field study, conducted by the Institute for Research Construction (National Research Council Canada) that illuminances larger than or equal to 150 lux were categorized as 'appreciable daylight'.[14] Furthermore, the Illuminating Engineering Society (IES) of North America recommends 50–100 lux, provided directly on the individual task area, as the general range of illuminance required for working with CRT screens.[15] In fact, during a survey of the work spaces of a computer hardware and software distribution company, where each of the offices contained at least two computers, measurements showed that most employees felt comfortable with a lighting level of around 100 lux (as opposed to the standard regulations of work places demanding 300–500 lux at desk level).[16] It has also been observed that people tend to tolerate much lower illuminance levels of daylight than artificial light, particularly in diminishing daylight conditions at the end of the day, such as continuing to read at levels as low as 50 lux.[17]

During a field study carried out by the Lawrence Berkeley National Laboratory (USA), office workers were allowed to create their own lighting environment by manually controlling blade angles of mechanical Venetian blinds and varying the intensity of electric lighting. The illuminances recorded during the study were in the range of 840–2146 lux in the morning and 782–1278 lux in the afternoon. This indicated that the occupants either preferred or tolerated higher light levels than those set by the automated control system (510 lux to 700 lux).[12]

Studies relating to office workers' impressions on daylight and lighting indicated that most office occupants wanted to work under some form of daylighting. However, in heavily glazed offices, people were less satisfied due to the high levels of daylight provision and the associated propensity for discomfort.[18,19] While noting that satisfaction with daylight is a complicated issue depending on many other factors such as facade orientation, obstructions, and the effectiveness of blinds, it is regarded that levels of daylight that are considered too low may easily be supplemented by electric lighting, whereas levels that are too high are associated with problems that are more complex to deal with (for example, glare and overheating).[19] In fact, occupant surveys have uncovered shortcomings for conventional design practice and have expanded the definition of an adequate office environment.[20] For example, variation in daylight levels is considered desirable provided that the range in experienced levels is not too great. Occupants prefer a space with a variation in the natural light pattern, and where they have a slightly higher task illuminance than the general surround illuminance, their visual perception can be enhanced.[20,21] Furthermore, researchers have noticed that lighting levels that are higher than the typical design workplane illuminance level (e.g., 500 lux) are tolerated by the occupants unless there is glare or direct sun, in which case the occupants may opt to operate the shading device.[22] Observations made by Roache over several weeks suggested that the visual environment, when facing a computer workstation which was at a right angle to the window (as is recommended), was reasonably comfortable when the working plane illuminance was below 1800 lux.[10,23] During that same experiment, it was noted that the daylight illuminance range of 700–1800 lux appeared to be acceptable for both computer and paper-oriented tasks.

A distillation of the authors' survey of published findings on occupant preferences and behaviour reads as follows:

- Daylight illuminances less than 100 lux are generally considered insufficient to be either the sole source of illumination or to contribute significantly to artificial lighting.

- Daylight illuminances in the range of 100–500 lux are considered effective either as the sole source of illumination or in conjunction with artificial lighting.
- Daylight illuminances in the range of 500–2000 lux are often perceived either as desirable or at least tolerable.
- Daylight illuminances higher than 2000 lux are likely to produce visual or thermal discomfort, or both.

In consequence, any daylight illuminance in the range 100–2000 lux should be considered as 'useful' to the illumination of the space. As noted earlier, the illuminated area needs to be considered in its entirety. Thus, in evaluating time-varying daylight illuminances across the work plane, 'useful daylight illuminance' is said to occur whenever *all* the illuminances fall within the range 100–2000 lux. As noted earlier, to be meaningful, the assessment of a daylit space must be based on time-varying daylight illuminances for an entire year at a time-step of an hour or shorter. A daylighting analysis founded on the percentage of the working year for which useful daylight illuminance occurs is described in the following section.

3.2 Determination of useful daylight illuminance: unshaded south-facing glazing

The raw illuminance data presented in Section 2 was processed to derive the percentage of the working year for which useful daylight illuminances occurred. The work plane area was taken to occupy the central 4 m 'core' of the 6 m deep office space (Figure 2). In normal usage, it is unlikely that the work plane area would extend from immediately adjacent to the glazing at the 'front' of the office to right up to the wall at the 'back'. The precise apportioning of the work plane area is arbitrary and does not affect the sense of the evaluation that follows.

The raw illuminance data for all the daylight hours in the working year were scanned and every occurrence of useful daylight illuminance across the core work plane area (i.e., $100 \leq E_{\text{core}} \leq 2000$) was counted. Useful daylight illuminance occurred for 17.6% of the working year (643 out of 3650 hours). The causes for not achieving UDI were as follows:

- for 64.1% of the working year there were instances where one or more of the core work plane illuminances was greater than 2000 lux
- for 8.7% of the working year there were instances where one or more of the core work plane illuminances was less than 100 lux, and
- for 9.6% of the working year there was no daylight.

Note that there is an additional theoretical cause for not achieving UDI. This is when illuminances both greater than 2000 lux and less than 100 lux occur at the same instant in time across the core work plane area. This did not occur at any time for the scenario described above (this is only likely to happen for an office space which has unrealistically low reflectivity walls or ceiling or which is very deep plan). Thus, the principal cause for not achieving UDI was the large number of instances where the illuminance exceeded 2000 lux. This is to be expected from the plots shown in Figures 4 and 5. Note however that UDI could not have been deduced from either of these plots because the calculation points are treated independently.

It is proposed here that the three UDI metrics for: achieved (P_{udi}), exceeded ($P_{E>2k}$) and fell-short ($P_{E<100}$), are robust indicators of the actual daylighting provision for an internal space. The main purpose of the UDI scheme is to allow ready comparison of multiple design options based on their daylighting performance. This is demonstrated in the next section.

3.3 UDI: sensitivity to glazing transmission and office orientation

The procedure described above was repeated for the same office geometry but now for all combinations (i.e., design variants) of clear, mid and heavy tint (double) glazings and four building orientations. The tinted glazings were based on Pilkington AntiSun Green and AntiSun Bronze. The transmittance used to model the glazings was taken from the Pilkington handbook: 0.76 (clear); 0.63 (AntiSun Green); and, 0.44 (AntiSun Bronze). The building orientations used were the four cardinal points of the compass i.e., north, east, south, and west. The results are shown in Table 1. The UDI metrics for south-facing clear glazing are repeated for comparison. The sensitivity in the UDI metrics to the two design parameters (glazing tint and office orientation) is easy to discern. It might reasonably be expected that a well daylit space is one where the achieved UDI is maximized at the expense of the other two metrics (exceeded and fell-short). The effect of varying glazing tint for the office facing south is readily apparent. But even the heaviest tint (i.e., lowest transmission) glazing results in UDI exceedences for half of the working year (south facing glazing). Based on the field studies noted in Section 3.1, illuminances greater than 2000 lux are likely to cause occupants to draw blinds or shading devices. Thus, in real office spaces, the UDI metrics given in Table 1 will change in response to occupant behaviour. How this modifies the UDI metrics is described in the following section.

3.4 Blind operation and UDI

The intention here is to show how the UDI paradigm, as a matter of course, accounts for any daylight modulating system e.g., blinds, shading devices, electrochromic glazings, etc. The example given below is for an office with a typical Venetian blind. A simple 'shutter' model was devised to simulate the 'ideal' manual operation of blinds by the office occupants whenever the daylight illuminance predicted anywhere along the core work plane exceeded 2000 lux. As this model was devised to mimic the manual operation of blinds, it was considered that discomfort experienced at any point along the length of the office could prompt the occupant at that point to operate the blinds. The operation is termed 'ideal' because it was modelled as perfectly daylight-linked i.e., the blinds were always shut in response to illuminances greater than 2000 lux and always retracted whenever 2000 lux would not be achieved. In actuality, this control model could not be said to offer realism since there is no stochastic

Table 1 The three UDI metrics (percentage of the working year where UDI is achieved, exceeded and fell-short) for 12 glazing-orientation combinations

P_{udi} % Achieved; $P_{E>2k}$ % Exceeded / $P_{E<100}$ % Fell-short	North		East		South		West	
	P_{udi}	$P_{E>2k}$ / $P_{E<100}$	P_{udi}	$P_{E>2k}$ / $P_{E<100}$	P_{udi}	$P_{E>2k}$ / $P_{E<100}$	P_{udi}	$P_{E>2k}$ / $P_{E<100}$
Clear	43.6	35.7 / 11.2	36.3	44.5 / 9.6	17.6	64.1 / 8.7	24.5	55.9 / 10.0
Medium tint	51.4	24.9 / 14.1	42.7	35.6 / 12.1	20.2	59.6 / 10.6	29.3	48.6 / 12.4
Heavy tint	63.1	5.5 / 21.8	51.6	20.1 / 18.7	25.6	50.2 / 14.6	37.7	35.5 / 17.2

(i.e., human) component to the operation. However, that is of minor importance here. The purpose of the model is simply to provide some dynamic operation of blinds in response to illumination levels. Furthermore, an uncomplicated, deterministic modulation to the daylight is preferred for this preliminary investigation of the UDI paradigm.

Measurements in office spaces have found that approximately 20% of incident daylight penetrates Venetian blinds when they are fully drawn and the slat angle is $\sim 60^{\circ}$ which is considered 'closed'.[24] Simulation tests were carried out modelling, in detail, a Venetian blinds system installed on the window of the office model shown in Figure 2. The results showed that, after removing the direct sun component (if present), the total of the remaining daylight components penetrating fully-drawn Venetian blinds was indeed very close to 20% of that which would arrive inside the office if there were no blinds. Therefore, it was decided that fully drawn Venetian blinds were to be modelled in this study as a filter which first removed any existing direct sun component from the transmitted daylight and then reduced the transmission of the remaining daylight components (i.e., direct sky, indirect sky, and indirect sun) by 80%. The illuminances for unshaded glazing were re-used with the filter applied to mimic the effect of drawn blinds.[9]

The hourly daylight illuminances from the unshaded glazing model used in the previous section were scanned again. This time, when the daylight illuminance at one or more of the calculation points along the core work plane exceeded 2000 lux, then all the illuminances for that hour were diminished to mimic the effect of blinds i.e., the direct sun component was removed and the remainder reduced by 80%. The UDI was evaluated from these illuminances as before. This was done for all combinations of glazing tint and orientation. The results are presented in Table 2. For south facing, clear glazing, the occurrence of UDI increases threefold compared to the unshaded case, as does the occurrence of illuminances less than 100 lux. It is evident that, employing this admittedly idealized blind control, clear glazing always offers the highest occurrences of achieved UDI and the lowest occurrences where the daylight fell short of achieving UDI.

4. UDI and electric lighting consumption: what is the relation?

It is reasonable to expect that high occurrences of UDI might be associated with low levels of electric lighting consumption. A simple correlation between UDI and electric lighting for arbitrary cases is unlikely because

Table 2 The three UDI metrics (percentage of the working year where UDI is achieved, exceeded and fell-short) for the office with blinds. All 12 glazing-orientation combinations

P_{udi} % Achieved	$P_{E>2k}$ % Exceeded / $P_{E<100}$ % Fell-short	North		East		South		West	
	Clear	35.3	0 / 55.2	42.6	0 / 47.8	61.4	0.8 / 28.2	52.6	2.0 / 35.8
	Medium tint	28.2	0 / 62.2	38.2	0 / 52.3	58.6	0 / 31.8	49.2	0.2 / 41.1
	Heavy tint	29.3	0 / 61.2	34.8	0 / 55.6	51.7	0 / 38.7	42.8	0 / 47.7

the latter is strongly dependant on the control system used for the luminaire e.g., on–off switching, dimming, etc. However, where the control system type for the luminaire and blinds are kept constant, significant correlations were suspected from preliminary results of a handful of cases for one climate locale. Evidence for a relation was investigated by evaluating the annual electric lighting consumption for each design variant using two lighting control models. The test for a correlation was expanded further to include UDI and electric lighting consumption predicted for a number of different locales, in both the north and south hemispheres. A description of the electric lighting models and meteorological datasets follows.

4.1 Electric lighting models

The office was taken to be illuminated by three luminaires located at 1 m, 3 m and 5 m from the window, to cover, respectively, the front, middle, and back zones of the office. The lighting controls models used were:

- Daylight-linked on–off switching. The luminaire was taken to be on whenever the daylight illuminance at the control point for that zone was below 500 lux, and off whenever it was above 500 lux.
- Daylight linked top-up lighting. Each luminaire supplements whatever daylight is available to a set-point of 500 lux.

A value of 80 lm/W for the luminous efficacy of the electric lamps was used. The light output ratio of the luminaires (i.e., their efficiency) was taken to be 0.5. Each of the luminaires was considered to be controlled independently of the others according to the lighting requirement and the daylight illuminance of the office zone it illuminated. In addition, assuming a light loss factor of ~10% due to dirt and ageing depreciation, the average net luminous efficacy of the electric lighting system at workplane level was taken to be 36 lm/W for on–off switching. For dimming, a further 10% loss due to the control gear was included giving a net luminous efficacy of 33 lm/W.

4.2 Multiple climate locales

To broaden the examination of the relation between UDI and electric lighting consumption, the number of design variants was greatly expanded by increasing the number of climate locales from one to 14. Some of these were for low-latitude locales with a high incidence of clear sky conditions in the climate data. Others were for less sunny locales at higher latitudes. Eleven of the sites were in the northern hemisphere, the remaining three in the southern hemisphere. A listing of the locales for the climate datasets and their latitude and longitude coordinates is given in Table 3. The majority of these datasets are freely available from various web sites. For example, the Renewable Resource Data Centre (http://rredc.nrel.gov) lists over 200 climate datasets (known as TMY2) for the US. Each climate dataset is unique, and because illumination from the sun is considered, the predicted internal illuminance will depend strongly on the latitude as well as the building orientation. The sky model mixing function described in Mardaljevic[2] was used to generate hourly sky luminance distributions based on irradiation quantities in the climate datasets and the solar altitude. The mixing function

Table 3 Longitudes and latitudes of locations of studied weather files

Location	Latitude	Longitude
Almeria, Spain	36.83°N	2.45°W
Boulder, USA	40.02°N	105.25°W
Cairo, Egypt	30.05°N	31.25°E
Frankfurt, Germany	50.03°N	8.55°E
Glasgow, UK	55.87°N	4.43°W
Hong Kong, China	22.30°N	112.40°E
Kew, UK	51.47°N	0.28°W
Miami, USA	25.80°N	80.27°W
Nairobi, Kenya	1.28°S	36.82°E
Seattle, USA	47.45°N	122.30°W
Singapore, Singapore	1.30°N	103.80°E
St. Petersburg, Russia	59.92°N	30.25°E
Sydney, Australia	33.90°S	151.20°E
Wellington, New Zealand	41.30°S	174.78°E

was calibrated using UK data and it is probable that differences in the parameterization of the model might result for other climates. However, the intention here is not to address the relatively subtle effect that may result from re-calibration of the mixing function. Rather, it is to reveal the gross variations in the daylight illumination of the office space when subjected to a range of climates with very different prevailing characteristics e.g., St Petersburg (Russia) and Miami (USA). In addition to considering many climate locales, the number of building orientations was increased from four to 12 i.e., orientations from 0° (north) to 330° in steps of 30°.

Internal illuminances were predicted for all 504 combinations of: 14 climates; 12 orientations; and, three glazing tints. The electric lighting usage for each of the 504 design variants was predicted using:

- windows without blinds and on–off luminaire switching
- windows with 'ideal' blinds and on–off luminaire switching; and
- windows with 'ideal' blinds and 'top-up' luminaire switching.

The results are presented as scatter plots of annual electric lighting usage versus achieved UDI. The predictions for the window without blinds are given in Figure 6(a). The two cases for the window with blinds are given in Figure 6(b). Different symbols are used for each of the three glazing tints.

For windows without blinds, there is a strong positive correlation between electric lighting usage and achieved UDI (Figure 6a). This occurs because, for the majority of the design variants, there is over-provision of daylight i.e., daylight illuminances exceed 2000 lux at one or more points across the core of the office space for much of the year. The correlation is weakest for heavy tint glazings. However, as noted in Section 3.1, illuminances higher than 2000 lux are likely to cause occupants to trigger shading mechanisms. Thus, the apparent low annual energy use for electric lighting in the office without blinds is, in practice, unattainable on the grounds of visual and thermal comfort. Nonetheless, it is instructive to examine further the achieved UDI values for each glazing type independent of the electric lighting usage, and to make some comparison with what a daylight factor analysis might disclose about the daylighting performance of the office space. The ranges (i.e., minimum to maximum) for the achieved UDIs were: 3% to 46% for clear double glazing (DG); 6% to 61% for AntiSun Green; and, 16% to 82% for AntiSun Bronze. The variation in the achieved UDI for any one of the glazing types results from the 168 different combinations of orientation and local climate. The ratio of the maximum to minimum achieved UDIs for each glazing type was: ~15 (clear DG); ~10 (AntiSun Green); and, ~5 (AntiSun Bronze). For each glazing type, an enormous variation in daylighting performance (i.e., achieved UDI) was predicted that resulted solely from the effects of orientation and local climate, which, of course, are not accounted for in a daylight factor evaluation. The ratio of the maximum to minimum achieved UDI across all combinations (including now, glazing type) was ~27. In stark contrast, an evaluation based on daylight factors would have shown variation in performance with respect to glazing type only. Furthermore, the ratio in any predicted daylight factors across the three glazing types would be only ~1.7 since is it dependant solely on the glazing transmission (the office dimensions and surface reflectivities are fixed). To summarize, the UDI paradigm discloses a factor 27 difference in the daylight performance of the office space across all scenarios (orientation, local climate and glazing type) whereas the ratio in any predicted daylight factors across the three scenarios to which the approach is sensitive (glazing type only) would be less than two. The determination of the sensitivity of key quantities to basic design parameters is the foundation of buildings' performance evaluation. Insensitivity to

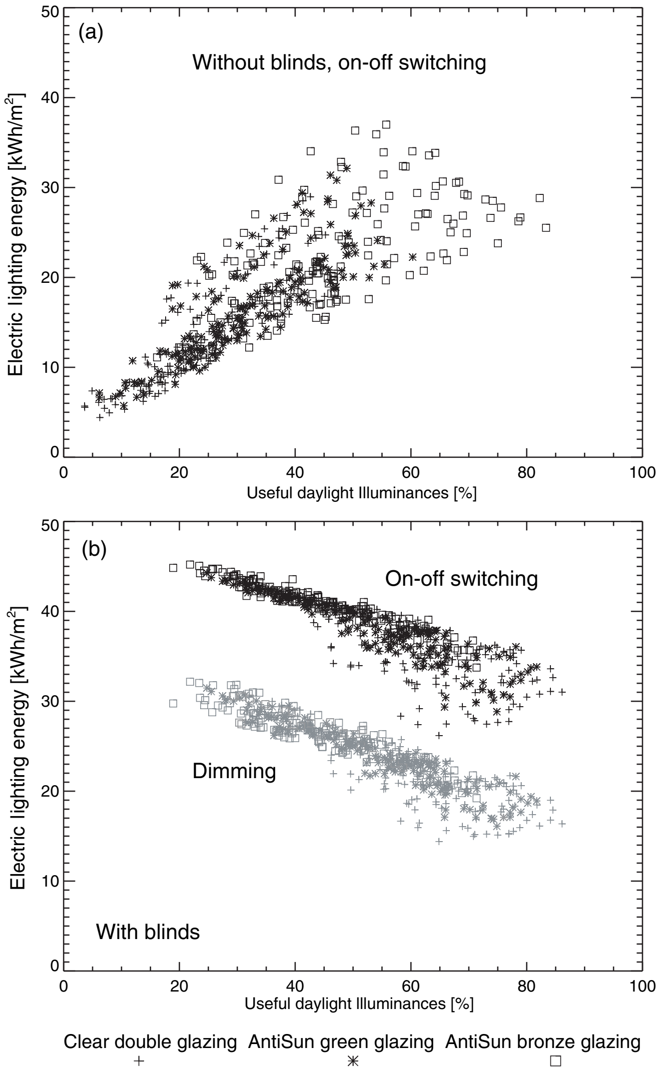

Figure 6 Annual electric energy consumption for lighting versus achieved UDI for all combinations of: three glazing types; 12 orientations and 14 climate TRYs

climate and orientation is, of course, an intrinsic property of the standard daylight factor approach. What is perhaps surprising is the marked degree of the insensitivity, both in absolute terms and in comparison with that offered by the UDI paradigm.

To return to the examination of the UDI metrics for the office space with blinds in operation to protect against high levels of illuminance, there is now an anti-correlation between annual electric lighting usage and achieved UDI for each of the luminaire switching models (Figure 6b). Note that, for any given design variant, the achieved UDI (ordinate) is the same for both the on–off and top-up lighting control models—it is only the annual electric lighting consumption that changes. The correlations in Figure 6(b) suggest that high levels of UDI in offices with operable shading devices are associated with lower levels of electric lighting usage. Furthermore, this relation is general and does not depend on the locale or orientation of the building.

5. Discussion

The useful daylight illuminance paradigm preserves much of the interpretive simplicity of the familiar daylight factor approach—only three metrics are needed to characterize the daylighting performance of an internal space in its entirety, including the propensity for discomfort due to high levels of illumination. Unlike daylight factors however, the useful daylight illuminance metrics are based on absolute values of time-varying daylight illumination for a period of a full year. The range used to define the limits of useful daylight illuminance is based on the latest data from field studies of occupant behaviour under daylit conditions. Thus the UDI paradigm offers a considerable step towards an interpretive framework for daylighting that is founded both on realistic measures of absolute illuminance and on realistic models for occupant behaviour.

In contrast to measures of daylight autonomy, the UDI paradigm gives significance to those daylight illuminances below a design threshold (e.g., 500 lux), but which are nevertheless known to be valued by occupants and which also have the potential to displace all or part of the electric lighting. This aspect of the UDI formulation may be especially valuable for the assessment of deep-plan spaces with adjoining atria or light-wells such as the Coventry University Library.[25] The UDI paradigm is ideally suited for the assessment of any building design where daylight re-direction is a feature. Furthermore, its simplicity allows for rapid comparative assessment of any number of design variants. For example, the sensitivity of the UDI metrics to changes in the dimension(s) of an external overhang would help to optimize its design in terms of both solar shading (the $P_{E>2k}$ metric) and daylighting (the P_{udi} metric). The strong anti-correlation shown in Figure 6(b) suggests that high levels of achieved UDI (P_{udi}) are an indicator of low energy consumption for electric lighting in offices where either shading devices or some form of solar control are in operation.

There is little doubt that time-varying illuminance predictions, founded on standard meteorological datasets, offer a more realistic account of true daylighting conditions than the highly idealized daylight factor approach. The UDI paradigm offers the means to communicate the significant characteristics of time-varying illuminance data in a concise and readily intelligible form. Because of this interpretive simplicity, it is hoped that the UDI paradigm might help to promote more realistic modelling and analysis of daylight in buildings than has been the case to date.

The authors acknowledge that UDI is a 'work in progress' and that further calibration of the parameters needs to be carried out. For large daylit spaces, particularly those where daylight enters from more than one direction (e.g., through light-wells, atria, etc.), it may be more useful to determine the three UDI metrics at each point in the calculation plane independently rather than across a line or area. This could be useful for zoning large areas in terms of daylight availability and for identifying locations most at risk from excessive daylight illumination. Further studies employing the UDI paradigm in various contexts (e.g., for a light well and an office with electrochromic glazing) are underway and will be reported on in due course.

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Discussion

Comment on 'Useful daylight illuminance: a new paradigm for assessing daylight in buildings' by A Nabil and J Mardaljevic

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Daylight assessment theory is currently at a crossroads:

- Whether to prolong and apply anew the Daylight Factor (DF) criterion with its ratio based either on the traditional uniform or overcast sky luminance patterns, or expressed in the form of the Daylight Coefficient (DC) concept respecting arbitrary luminance distributions in a range of realistic skies with the sun present or absent,
- Whether to change the daylight design and assessment system to absolute illuminances in lux with their changes in annual profiles to simulate local seasonal and daily variations. This is the track followed by the authors and enhanced with their Useful Daylight Illuminance (UDI) contribution where they apply a general approach coupled also with DC use.

However, there are several obstacles to be overcome. These are:

- How representative are 'averaged' hourly irradiance or TRY datasets, when owing to rapid cloud movements and sky luminance patterns the momentary sunlight and skylight situations are unstable, so characteristic for daylighting?
- Can irradiance data from a few observatory records (e.g., Kew in UK) serve as bases for building design in different countries?
- Is the UDI concept valid for any daylight climate from the arctic to the tropics?

The DC criterion is a valuable concept when a set of interior illuminances needs to be calculated under several CIE General Sky Standards[1] and when the simulation of annual UDI profiles is required. However, after the original DC concept based on the sky luminance element alone was supplemented with direct sunlight, the DC matrix became quite complex owing to there being four illuminance components with many differently interacting sun positions and sun luminance changes together with their effects on differently orientated windows and exterior obstructions.

Thus the reader of this paper will question the simplicity of the computer model in Section 2.2 and wonder whether the authors' statement in Section 4.2 that DCs calculated in 12 surface elements on the working plane 'are invariant to orientation...furthermore once computed, DCs can be re-used with any number of climate datasets to rapidly generate internal illuminance predictions for various locales' is well founded.

There have to be at least several assumptions, not mentioned by the authors e.g., free horizon and external terrain or obstruction setting. What about reflectances and sunshine duration in different climates, etc? Also, and this is of especial significance, the general